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Original Research

Effect of the Digital Economy on Urban Green Development: Empirical Evidence from 284 Cities of China

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Abstract

To investigate the impact of the digital economy on urban green development and its fluctuations, the entropy method is employed to measure the degrees of the digital economy and green development in 284 cities of China during 2013 to 2019. A panel fixed-effect model is established for the exploration of how the digital economy affects urban green development. The results indicate: (1) Throughout the research period, notable variations were observed in digital economy and green development levels among cities, both of which demonstrated an upward trajectory overall. After undergoing several robustness tests, it is evident that the digital economy plays a significant role in advancing urban green development. (2) The impact of the digital economy on urban green development varies due to differences in urban resource endowments and geographical locations. In non-resource-based cities and the eastern regions, the positive influence of the digital economy on urban green development is more pronounced and significant. (3) The effect of the digital economy on urban green development does not follow straight-line characteristics. When the digital economy level attains a specific threshold, its positive impact will notably intensify. The results aid in shaping specific policies for different regions, promoting digital economic growth, and facilitating the urban green transformation.

Keywords: digital economy, urban green development, threshold effect, heterogeneity

Introduction

In recent years, with energy shortages and environmental pollution becoming increasingly the focus of global attention, green development has become a new trend in global development [1]. Green development seeks a balance between people and the ecological environment, prioritizing sustainable growth that centers on protecting the ecological environment [2]. The requirement for "accelerating the green transformation of the development model" and "promoting the establishment of a green and low-carbon production and lifestyle" was clearly emphasized by the Chinese government. Currently, China is in a critical stage of high-quality development. Green development, which is one of the elements of high-quality

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development, is an important support for achieving high-quality urban economic growth.

Meanwhile, advanced digital technology is quietly changing everything. Despite the adverse environment of global pandemic spread and economic downturn, China's digital economy has been growing rapidly with an average yearly growth of 14%, exceeding GDP growth by about 5 percentage points [3]. As a new mode of economic development, the digital economy has environmentally friendly characteristics compared with the traditional economy. Under the digital environment, the implementation of various information technologies has created convenient and efficient channels for information exchange, giving rise to new economic forms such as the platform economy, accelerating economic structural transformation, and more accurately meeting the requirements of green development [4]. A crucial avenue for the amalgamated growth of manufacturing and service sectors is served by the digital economy, fostering the establishment of a more secure, steady, and effective industrial network [5], providing a brand-new approach and feasible path for the country to fulfill the greenization goal. At present, digitization has permeated all sectors of the economy and society of China, becoming one of the key forces driving technological innovation and efficiency improvement [6]. The Chinese government attaches great importance to the development of the digital economy, as highlighted in the Report on the Work of the Government 2023, which specifically emphasizes the need to vigorously develop the digital economy. Can the digital economy truly become a "magic weapon" for solving ecological and environmental problems? Cities are the most active areas for socio-economic development and an important carrier of the internet-based economy, playing a key part in accomplishing high quality development [7].

To verify whether the digital economy is beneficial for green development in cities and whether its effect varies in different types of cities, this study selects 284 cities in China from 2013 to 2019 as samples. Based on scientifically measuring the levels of the two variables in these cities, this study empirically tests the impact of the digital economy on urban green development. Furthermore, it analyzes the heterogeneous impact of the digital economy on urban green development in different cities based on their geographical locations and resource endowment conditions. The aim is to comprehensively understand the current status of China's digital economy and green development at the urban level and provide guidance for policy design and implementation.

Literature Review

Digital Economy

American scholar Tapscott [8] proposed the term "digital economy" (hereinafter referred to as Dige in this paper for brevity) in his work first, believing it to be a new developing mode that has emerged along with the widespread application of information technology in various industries of the social economy. Later, "digital divide" was pronounced as a derived concept [9]. Regarding the digital economy, existing research focuses more on the evaluation of the Dige [10], and its economic and social effects. Some scholars pointed out that digitization has optimized resource allocation, upgraded consumer demand, accurately matched the relationship between suppliers and consumers, and improved the performance and TFP of enterprises [11]. With profit from digital finance, financial difficulties can be alleviated, so that enterprises may expand their production scale [12, 13]. Scholars also examined the policy effectiveness of the country by using the generalized DID model and found that the Dige has improved total factor productivity through technological progress [14]. Scholars also focused on the correlation between Dige and economic activities, and explored the mechanism that digital economy uses to promote economic growth [15, 16]. Other scholars found that Dige significantly promotes productivity, one of the important reasons being that information infrastructure promotes the full utilization of factors and cost reduction [17].

Green Development

The green development (hereinafter referred to as Gde in this paper for brevity) is mainly proposed by scholars on the basis of criticizing traditional development models. The primary focus of research on green development is the understanding of its connotations. Current understanding of green development mainly includes reducing carbon emissions during economic development, promoting green economic growth, and inclusive green development [18, 19]. Although Chinese scholars have different understandings toward the connotation of green development, they generally believe that it is a sustainable production and lifestyle characterized by resource conservation, environmental friendliness, and ecological protection under resource and environmental constraints, with the aim of maximizing economic, social, and ecological benefits [20, 21]. The next research focus is to establish a reasonable evaluation index system and conduct measurement analysis scientifically. The framework model containing economic, social, and environmental factors constructed by the United Nations Commission on Sustainable Development is a relatively comprehensive green development evaluation indicator system at present. A number of researchers have counted and measured the green economy or green development capacity based on it [22, 23]. Based on this system, some scholars include environmental, social, and economic systems in the accounting framework, and ultimately evaluate the sustainability of urban areas in the country [24]. The influencing factors and economic effects of green development are also focused on academic attention [25-28].

The Relationship between Dige and Gde

With the continuous infiltration of data elements in various industries, the attention of scholars has gradually shifted towards the relationship between green development under the background of digitization. The ongoing studies primarily center on assessing the influence of Dige or a specific aspect of it on urban environmental pollution, improvement of air quality, and overall green productivity. Some scholars have taken the implementation of the "Broadband China" policy in 2014 as a quasi-natural experiment to examine the impact of new infrastructure construction on urban carbon emissions. According to their study, the level of urban carbon emissions was notably decreased by the establishment of new infrastructure, which stimulated the advancement of Dige and enhanced industrial configuration [29]. Likewise, the "Broadband China" initiative was considered as a quasi-natural trial by certain academics, who discovered that the digital economy, through its impact on industrial output and residents' way of life, lessened the release of significant environmental pollutants like sulfur dioxide [30]. Also, the "Broadband China" initiative was considered as a quasi-natural trial by certain academics, who discovered that the Dige, through its function on industrial output and residents' way of life, lessened the release of significant environmental pollutants like sulfur dioxide [31]. Moreover, the analysis of how the Dige affects the eco-friendly advancement of a particular industry or field has been concentrated on by certain researchers [32].

Through a review of existing literature, it can be found that the current examination of the relationship between the Dige and Gde tends to focus more on certain aspects, lacking the integration of production, ecology, and livelihood within a holistic framework to systematically investigate the relationship between the digitization and environment. Besides, the characteristics of the relationship between the Dige and Gde is also relatively insufficient. In comparison with previous studies, this paper may make the following marginal contributions: firstly, using an index system that considers production, ecology, and livelihood aspects to gauge the degree of Gde and methodically explore the connection between the Dige and Gde within cities, and focus on exploring the nonlinear characteristics of the impact of digital economy on urban green development. Secondly, categorizing sample cities based on resource endowment and geographical location is important, enabling a comprehensive examination of the varied effects of the Dige on the advancement of urban Gde.

Theoretical Analysis and Research Hypotheses

The Promotional Effect of the Dige on Urban Gde

Urban green development is the process of achieving the mode of green production, green lifestyle, and inclusive social environment within the carrying capacity of economy, society, and environment, and taking the path of intensive, intelligent, and environmentally friendly development [33]. As an advanced form of economic and social development, the digital economy, represented by information industries such as 5G, big data, and artificial intelligence, continuously integrates with various aspects of urban development. It plays an important role in infrastructure transformation, industrial upgrading, social and environmental governance, and gradually becomes a new driving force of urban green development [34].

Firstly, the Dige takes digital knowledge and information as key production factors, promotes the penetration and integration of digital technology and the real economy through industrial digitization and digital industrialization, supports the optimization and upgrading of traditional industries, improves the utilization efficiency of production factors such as capital, labor, and energy, and promotes the intensive utilization of resources and efficient output in the production field [35]. Through digital industrialization, new forms and new models are constantly emerging, such as the platform economy, which promotes information flow aggregation to achieve efficient connections between supply and demand, and helps urban economic development and optimization of factor allocation [36].

Secondly, the development of Dige plays an important role in defending the urban ecological environment. On the one hand, the development of the digital economy is conducive to strengthening the real-time acquisition, analysis, and judgment of urban ecological environment data such as water, gas, soil, noise, and radiation, in order to timely grasp the urban ecological quality, as well as repair and improve environmental problems. On the other hand, services developed with digital technology, such as digital financial services, have innovatively changed the traditional way of information transmission and business processing [37]. Through online platforms, non-contact transactions are achieved, reducing energy consumption and carbon emissions such as paper and transportation, guiding green consumption among residents, and enhancing their participation in environmental protection.

Thirdly, the Dige promotes the widespread application of digital technology in urban life, promotes the intelligence, convenience, and inclusiveness of public facilities and services, and improves the quality of urban life. On the one hand, the application of digital technology has broken the geographical limitations of public services, enabling them to be replicated and transmitted, such as online healthcare and distance education. On the other hand, the application of digital technology in fields such as power grids, transportation, and municipal governance has promoted the construction of smart grids and intelligent transportation systems, effectively solving problems such as information asymmetry and structural mismatch between supply and demand, and allocating resources and urban roads more scientifically and reasonably. Moreover, the development of the digital economy can help facilitate and intelligently manage urban communities, promote the construction of smart communities, and improve the quality of residents' daily life.

Nonlinear Effects of the Dige on Urban Gde

The Dige benefits from network effects as indicated by Reed's Law and Metcalfe's Law, and its network value will significantly increase as it reaches a certain level [38]. So, does the influence of the Dige on urban Gde also exhibit time-varying characteristics? Indeed, it has been verified by certain previous research that environmentally friendly economic expansion is actively fostered by the digital economy and that a threshold effect is present [39]. Economic growth is an important dimension for examining urban green development. It has also been validated by certain researchers that the degree of eco-friendly development in Chinese agriculture can be notably enhanced by the digital economy, and this catalyzing impact demonstrates a nonlinear characteristic of " increasing marginal effect ". A substantial capacity to enhance China's Green Total Factor Productivity (GTFP) is possessed by the Dige, and as the GTFP rises, the promotion effect of the Dige on urban GTFP increases as well [40, 41]. Consequently, it is posited that, as the Dige continues to advance, specific nonlinear characteristics may be demonstrated by its influence on the progress of urban Gde.

Based on the above discussion, this paper proposes the following research hypotheses:

Hypothesis 1: The digital economy significantly contributes to urban green development.

Hypothesis 2: With the continuous improvement of the digital economy, it has a non-linear effect toward the urban Gde.

Research Design

Baseline Model

To confirm the above hypotheses, a panel data fixed-effects model is employed by this paper for analyzing the influence of the Dige on Gde within urban areas. Referring to existing research [42], the following baseline econometric model is established:

$$Gde_{i,t} = \alpha_0 + \alpha_1 Dige_{i,t} + \alpha_c X_{i,t} + \mu_i + \delta_t + \xi_{i,t}$$

where $Gde_{i,t}$ denotes the level of green development comprehensive index of city i at year t, while $Dige_{i,t}$ stands for the value of digital economic comprehensive index of the same city at the same year, and $X_{i,t}$ expresses a series of control variables μ_i is the individual fixed effect of city i, δ_t reflects the time fixed effects at year t, and $\xi_{i,t}$ means the random disturbance term.

Definition and Measurement of Variables

Main Explanatory Variable

The main explanatory variable in this paper is the level of digital economic development (Dige). The digital economy takes knowledge and information as production factors and the Internet as a carrier to influence the traditional production mode through information technology, promoting the digital transformation of the economy and society. Drawing on existing research, this article focuses on the development of the Internet and selects six indicators from three aspects: digital infrastructure, data human resources, and digital transactions, forming a digital economy indicator system to measure the digital economy at the urban level [43]. The ratio of broadband internet access users among 100 individuals, the ratio of mobile phone users among 100 individuals, per capita telecommunications service revenue, the share of workers in information transmission, computer services, and software industries in the total employee count at the city's conclusion, the share of workers in transportation, warehousing, and postal services in the total employee count at the city's conclusion, and the China Digital Financial Inclusion Index are encompassed by these measures [44]. The entropy method is utilized for a comprehensive assessment, leading to the creation of a composite index that measures the extent of digital economic development within cities, as depicted in Table 1.

Dependent Variable

The dependent variable is the urban green development (Gde). Green development, as one of the important ways to achieve sustainable development, is essential to break free from excessive dependence on resource consumption under the constraints of resource and environmental carrying capacity, and to achieve the coordination and unity among moderate economic and social development, rational utilization of energy, and harmonious coexistence between humans and nature [45]. This requires green development to not only highlight the characteristics of green and clean, but also to implement the core principle of development [46]. Based on this connotation, referring to the research of pertinent scholars [47], an inclusive index system for urban green development, covering 18 indicators across three domains: production, ecology, and livelihood, is formulated in this paper. These indicators include three dimensions which are economic development, environmental protection, and social progress. Entropy method is used to measure the level of Gde. A detailed index system is provided in Table 1.

Control Variables

Considering the potential impact on the robustness of empirical results coming from other factors, this paper includes six control variables as following: foreign direct investment (Fdi), industrial structure (Ind), financial development (Fin), environmental regulation (Env), urbanization level (Urb), and human capital level (Hum). More precisely, the Fdi is gauged by the ratio of foreign direct investment originating from both foreign entities and regions like Hong Kong, Macao, and Taiwan in comparison to the GDP. The Ind is characterized by the proportion of added value of the secondary industry to GDP. The Fin is measured by the proportion of various RMB loan balances of financial institutions to GDP at the end of the year. The Env is expressed by the comprehensive utilization rate of industrial solid waste. The Urb is quantified by the proportion of the population residing in urban areas in relation to the total city population. The Hum is served by the proportion of the overall student population enrolled in universities relative to the total workforce engaged in all the three industries.

Data Sources and Analysis

Except for the Digital Inclusive Finance Index from the Peking University Digital Finance Research Center, most of the data are obtained from "China Urban Statistics Yearbook," various regional statistical yearbooks, and economic and social development

Table 1. Comprehensive index of digital economy and urban green development.

Primary Index	Dimensions	Secondary Index	Indicator Attribute
Digital economy (Dige)	Digital infrastructure	Ratio of broadband internet access users among 100 individuals	+
		Ratio of mobile phone users among 100 individuals	+
	Data human resources	Proportion of employees in information transmission, computer services and software industry	+
		Proportion of employees in transportation, warehousing, and postal industries	+
	Digital transactions	Per capita telecommunications service income	+
		the China Digital Financial Inclusion Index	+
Urban green development (Gde)	Economic development	Per capita GDP	+
		GDP growth rate	+
		Labor productivity	+
		Proportion of tertiary industry	+
		Government technology expenditure	+
	Environmental protection	Electricity consumption per unit of GDP	-
		Total water supply per unit GDP	-
		Construction land per unit GDP	-
		Utilization rate of general industrial solid waste	+
		Centralized processing rate of sewage	+
		Harmless treatment rate of domestic garbage	+
		Removal rate of SO_2	+
	Social progress	Green coverage rate in built-up areas	+
		Bus ownership per 10000 people	+
		Public Library Collection per 100 People	+
		Per capita urban road area	+
		Per capita number of beds in medical and health institutions	+
		Internet penetration rate	+

Table 2. Descriptive statistical results of main variables.

Variables	Observations	Mean	Standard Deviation	Min	Max
Gde	1988	0.4085	0.0520	0.1353	0.6035
Dige	1988	0.1665	0.0725	0.0393	0.5415
Fdi	1988	0.0167	0.0173	0	0.2103
Ind	1988	45.542	3.5110	39.765	51.039
lFin	1988	17.508	0.2163	17.169	17.821
Env	1988	79.987	2.7136	75.904	83.143
Urb	1988	0.3751	0.0184	0.3485	0.4093
Hum	1988	0.2742	0.3323	0.1241	1.0873

statistical bulletins. Linear interpolation method is used to fill the missing values. Table 2 reports the overall characteristics of the data.

Results and Discussion

Baseline Regression Results Analysis

Table 3 reports the regression results of the baseline model. The coefficient of Dige is consistently significant and positive after gradually introducing control variables, implying that the Dige can significantly promote urban Gde. Hypothesis 1 is thus confirmed. Additionally, the coefficients of the control variables generally align with expectations. The rational foreign investment, financial development, and environmental regulation from the government are contributing to green development. The continuous improvement and innovation of financial products and services provide abundant financing channels for enterprises, reducing financing costs. Moreover, reasonable financial policies direct funds more toward green and high-tech industries, promoting urban green development. The proportion of the secondary industry, represented by manufacturing, has a negative impact on urban green development, indicating the need to further optimize the industrial structure and accelerate the transformation and upgrading of the manufacturing industry.

Nonlinear Effects Analysis

The baseline regression results show that the Dige has a significant impact on urban Gde. Will this impact exhibit different characteristics with the development of the digital economy, that is, whether there is a non-linear relationship between variables? Hansen's (1999) panel threshold regression model is employed by this paper to examine the possible nonlinear association [48]. "Threshold regression" essentially aims to have threshold variables identified among those with causal relationships, have the threshold values estimated based on sample data, and have significant differences tested by the parameters divided by the threshold values [49]. The panel threshold regression model is established by this paper as follows (the number of thresholds will be determined based on the sample data during the actual testing):

$$Gde_{i,t} = \phi_0 + \phi_1 Dige_{i,t} \times I(TH_{i,t} \leq \theta) + \phi_2 Dige_{i,t} \times I(TH_{i,t} > \theta) + \phi_i X_{i,t} + \mu_i + \delta_t + \xi_{it}$$

Where the threshold variable is denoted by $TH_{i,t}$ with the level of Dige development being chosen as the threshold variable for this particular study; I(•) is an indicator function that takes the value of 1 or 0; θ is the unknown threshold value.

To ensure the precision of the threshold estimation, the Bootstrap method is employed to ascertain the number of thresholds in the model. After 300 repeated samples, the variable Dige passed the dual-threshold existence test. Tables 4 and 5 show the existence and number of thresholds and the specific threshold value respectively.

Table 6 presents the specific threshold values and parameters during each period. When the level of Dige remains at or below the threshold value of 0.1406, a positive impact of the Dige on urban green development is indicated by a coefficient of 0.0985, yet it is not statistically significant. When the level of Dige is greater than 0.1406 but less than 0.1430, its impact on urban green development temporarily becomes negative. However, once it surpasses 0.1430, its impact on urban Gde turns positive again, with the coefficient increasing to 0.1553, and it is significant at the 5% significance level. This result demonstrates that the Dige generally promotes urban Gde, and this effect exhibits a nonlinear characteristic. Before the development of the digital economy reaches a certain level (0.1430), its positive promotion effect on urban green development is relatively weak, and may even show a negative effect in the short term. However, once the Dige reaches a certain level (0.1430), its promotion of urban green development will significantly increase. The need for electricity to support the functioning of digital infrastructure and the storage of extensive data could be attributed to this [50]. Additionally, digital products are widely popular and applied in various fields, and their updating and iteration speeds are fast. The utilization of raw materials will be amplified by the rise in consumer demand and will also necessitate waste recycling, which is unfavorable for the

Table 3. Baseline regression results.

Variables	Gde						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Dige	0.156***	0.158***	0.157***	0.154***	0.155***	0.115**	0.115**
	(0.0518)	(0.0517)	(0.0518)	(0.0516)	(0.0511)	(0.0491)	(0.0491)
Fdi		0.226***	0.227***	0.201**	0.203**	0.133*	0.133*
		(0.0854)	(0.0842)	(0.0843)	(0.0834)	(0.0801)	(0.0801)
Ind			-0.0049**	-0.0052**	-0.0056***	-0.0038*	-0.0038*
			(0.0021)	(0.0021)	(0.0021)	(0.0020)	(0.0020)
lFin				0.0298***	0.025***	0.0241***	0.0241***
				(0.00921)	(0.0092)	(0.0087)	(0.0087)
Env					0.0043***	0.0045***	0.0045***
					(7.17e-05)	(6.85e-05)	(6.85e-05)
Urb						-0.00203	-0.00203
						(0.00263)	(0.00263)
Hum							-0.637***
							(0.207)
City fixed effects	Y	Y	Y	Y	Y	Y	Y
Year fixed effects	Y	Y	Y	Y	Y	Y	Y
Constant	0.387***	0.429***	0.422***	0.464***	0.0132	0.0501	0.0382
	(0.00607)	(0.0151)	(0.0154)	(0.0235)	(0.141)	(0.140)	(0.134)
Observations	1,988	1,988	1,988	1,988	1,988	1,988	1,988
R^2	0.017	0.017	0.021	0.026	0.033	0.053	0.056
N	284	284	284	284	284	284	284

Note: Standard errors in parentheses; ***p<0.01, **p<0.05, *p<0.1.The same below.

Table 4. Threshold existence test.

Threshold variables	Test	F value	P-value	Critical value		
				10%	5%	1%
Dige	Single threshold value	19.42	0.0467	14.7123	18.3866	28.4722
	Double threshold value	23.32	0.0133	13.2111	16.0562	25.5889
	Triple threshold value	10.26	0.3267	22.5878	31.0002	37.9268

Table 5. Threshold estimates and 95% confidence interval.

Threshold variables	Threshold estimates	Confidence interval
Dige	0.1406	(0.1396, 0.1411)
	0.1430	(0.1383, 0.1433)

Table 6. Regression results of panel threshold model.

Variables	Coefficient	T value
Fdi	0.2087**	2.01
Ind	0.0264***	6.23
lFin	0.459***	5.98
Env	0.006***	7.23
Urb	-0.008	-0.18
Hum	-0.0089**	-2.26
Dige.I (Dige≤0.1406)	0.0985	1.19
Dige.I (0.1406<Dige≤0.1430)	-0.1589	-1.09
Dige.I (Dige>0.1430)	0.1553**	1.99
Constant	-9.3335***	-5.93
Observations	1,988	1,988
R^2	0.03242	0.03242

advancement of an eco-friendly economy [51]. Thus, Hypothesis 2 is verified.

Endogenous Processing

Firstly, using the systematic GMM estimation, we can alleviate endogeneity problems caused by the dependent variable and its lagged term. Secondly, instrumental variables are employed to alleviate endogeneity issues caused by the causal relationship between the dependent variable and the explanatory variable. This paper chose the historical instrumental variable, which is expressed by the interaction term of the quantity of post offices per million individuals in each city in 1984, and the preceding year's urban Internet penetration rate (Iv1), for analyzing the evolution of the Dige. In addition, the core explanatory variable Dige lagged one period is the second instrumental variable (Iv2). On the one hand, the historical level of postal and telecommunications development and the lagging level of the digital economy are both related to the current development of the digital economy. On the other hand, the level of green development in each region will not affect the previous year's digital economy and internet penetration rate. Table 7 displays the results of endogenous processing. Column (1) and column (3) represent the regression results of the instrumental variables in the first stage. The F-values of the two instrumental variables in the first stage are both greater than 10 and the Kleibergen-Paap rk Wald F statistics are greater than the critical value of 16.38 under a 10% bias, rejecting the weak instrumental variable hypothesis, and indicating that the selection of the instrumental variables is reasonable. The results of the second stage of instrumental variables in column (2) and column (4) indicate that, after identifying endogeneity issues,

Table 7. Endogenous processing results.

VARIABLES	(1)	(2)	(3)	(4)	(5)
	Dige	Gde	Dige	Gde	Gde
L.Gde					0.4846***
					(0.0614)
Dige		0.3164***		0.1978***	0.3379*
		(0.1059)		(0.0292)	(0.1907)
Iv1	0.0016***				
	(0.0001)				
Iv2			0.9268***		
			(0.0103)		
Controls	Y	Y	Y	Y	Y
City fixed effects	Y	Y	Y	Y	Y
Year fixed effects	Y	Y	Y	Y	Y
Wald		53.82		123.99	
AR(2)					0.440
Hansen					0.217
Constant	-0.189***	0.1119	0.0439***	0.0937***	0.1410*
	(0.0722)	(0.1591)	(0.0092)	(0.0249)	(0.0778)
Observations	1,522	1,522	1,660	1,660	1,660

digital economy still has a significant positive impact on green development, further verifying the rationality of hypothesis 1. Meanwhile, compared with the benchmark regression, it can be found that ignoring endogeneity issues would underestimate the promoting effect of the digital economy on green development. Column (5) displays the estimated results of the systematic GMM. It has passed the Arellano-Bond sequence correlation test and Hansen's test, and the coefficient of the explained variable lagged one period is significantly positive, showing the rationality of using systematic GMM estimation.

Robustness Tests

To further ensure the reliability of the research results, this paper employs the following four methods for robustness tests. First, replace the core explanatory variable. Citing relevant research, researchers utilize the principal component analysis technique to substitute the entropy weight method for gauging the degree of digital economic advancement [52]. Second, employing green development efficiency to characterize the explained variable. After investing in production factors such as labor, capital and energy, the economic society will obtain the expected output GDP, but at the same time, it will also produce unexpected outputs such as environmental pollution. A super-efficiency SBM model under global production technology conditions is used to measure the green development for robustness testing. Third, partial sample exclusion is considered. Directly administered municipalities and provincial capitals have better conditions in terms of infrastructure, resource allocation, and talent attraction compared to other cities, which can create a favorable environment for the development of the Dige and green transformation of urban economies, thereby affecting the accuracy of the results of this paper. Therefore, this paper excludes 30 regions, including 4 directly administered municipalities and 26 provincial capitals, for regression analysis. Fourth, the substitution of measurement methods. Considering the possible presence of serial correlation or heteroscedasticity in the data, this paper uses the Generalized Least Squares (GLS) to effectively estimate the existing data. Regardless of the approaches taken, the coefficients of Dige remain significantly positive as shown in Table 8, confirming that the conclusion of this paper still holds.

Heterogeneity Analysis

Urban Resource Endowment Heterogeneity Test

China is vast in its land scale, and each area is significantly different in its city types and abundance of resources. Different cities have different economic development modes and industrial structures, which may lead to heterogeneity in the impact of the Dige on the green transformation of urban economies. Based on the classification criteria for resource-based cities in the National Sustainable Development Plan for Resource-Based Cities (2013-2020) issued by the State Council, the 113 cities in the research sample are classified as resource-based cities, and the 171 cities are classified as non-resource-based cities for grouped regression, further exploring the heterogeneous impact of the Dige on green development in different types of cities. The regression results are shown in Table 9.

From the first two columns of Table 9, it can be seen that Dige has a positive impact on Gde to non-resource-based cities, which is significant at the 1% level; however, with resource-based cities, the effect is not significant. The possible reason is that the resource-based cities have developed a reliance on specific resource-based industries over long periods of economic development, making it difficult and time-consuming to adjust their industrial structure. Traditional resource-based industries are difficult to effectively integrate

Table 8. Robustness test regression results.

VARIABLES	(1) Replacing the core explanatory variable	(2) Replacing the explained variable	(3) Excluding samples of key cities	(4) GLS
Dige	0.0446***	0.2409*	0.0497**	0.272***
	(0.0135)	(0.1325)	(0.0224)	(0.0107)
Controls	Y	Y	Y	Y
City fixed effects	Y	Y	Y	Y
Year fixed effects	Y	Y	Y	Y
Constant	0.294***	-0.1510	0.398***	0.373***
	(0.0323)	(0.3604)	(0.0044)	(0.0015)
Observations	1,807	1923	1,613	1,811
R^2	0.038	0.044	0.038	0.190
N	279	276	250	279

Table 9. Heterogeneity test regression results.

VARIABLES	Gde				
	(1) Resource-based city	(2) Non-resource based city	(3) East	(4) Central	(5) West
Dige	0.0164	0.0830***	0.127***	-0.0380	0.0840*
	(0.0415)	(0.0302)	(0.0410)	(0.0363)	(0.0501)
Controls	Y	Y	Y	Y	Y
City fixed effects	Y	Y	Y	Y	Y
Year fixed effects	Y	Y	Y	Y	Y
Constant	0.392***	0.404***	0.445***	0.392***	0.378***
	(0.00757)	(0.0103)	(0.0149)	(0.0114)	(0.00937)
Observations	704	1,107	667	643	501
R^2	0.011	0.056	0.030	0.063	0.112
N	111	168	99	98	82

with digital technologies, unable to fully unleash the digital effects, thereby weakening the driving role of digitization. Conversely, non-resource-based cities have less reliance on resource-based industries, with more diverse industrial types. The rapid advancement of digitization can facilitate the transfer of production factors between different industries, beneficial for industrial structural adjustment and upgrading, thereby promoting the green transformation of these cities.

Analysis of Urban Location Heterogeneity

Considering China's extensive landmass and the substantial variations in developmental circumstances among different regions, a "digital divide" effect might be demonstrated by the influence of the Dige on urban green development [53]. Therefore, this study classifies the cities into three areas: the east, the central, and the west, to examine whether there is some difference about the impact in different geographical locations. The results of the grouped regression in the last three columns of Table 9 show the coefficient of Dige in the eastern region is 0.127, and is significant at the 1% level. In the western region, the coefficient turns to 0.084, and is significant at 10% level. This indicates that Dige plays an important and positive role in promoting the greenization of cities in both eastern and western areas, and, moreover, the positive effect in the eastern area is far more pronounced than in the western area. This might be because eastern cities have both policy and geographical advantages, which help import advanced elements including talents, technology, and information. The coefficient of Dige in the central area is negative and not significant.

Conclusions and Policy Implications

Conclusions

According to the above analysis, three conclusions can be drawn in this article: (1) Dige contributes to the promotion of urban green development, and the result remains valid after endogeneity processing and robustness tests. (2) Threshold regression reveals that, with the development of Dige, its promotion role toward urban Gde exhibits a nonlinear characteristic of increasing marginal effects overall. (3) Heterogeneity analysis indicates that green development is more prominently propelled by the digital economy in cities situated in the eastern regions and those not reliant on resource-based industries.

Policy Implications

First, fully utilize the advantages of digitization to promote the transformation of urban economies toward green mode. For example, there should be efforts to construct digital technology network platforms, establish regional information-sharing and interactive mechanisms, encourage and guide enterprises to fully utilize digital technology platforms for participation in communication and transactions, accelerate the circulation and interaction of innovative resources and data elements among cities, and promote the aggregation of economic entities in cyberspace. Fully leveraging network effects, promoting the technological spillover of advanced enterprises, accelerating the deep use of new technologies in cities, and advancing the collaborative development of enterprises should all be considered.

Second, facilitate the transition of regional economies to green development models. This can be achieved by enhancing the deep integration of digital technologies with various traditional industries, encouraging enterprises to carry out digital transformation of production processes and organizational structures, accelerating the formation of green development modes such as industrial intelligence, and improving the level of industrial digitalization. Establishing and improving a digital economic development system, creating a favorable atmosphere for innovation, nurturing and attracting digital talents, and enhancing the mastery of advanced technologies and data processing capabilities can help drive the green transformation of urban industrial structures.

Third, pay attention to the differences in the development situation of digitization as well as resource endowments in various areas, and formulate tailored policies for different cities. For instance, resource-based cities should gradually reduce their reliance on resource endowments, and encourage enterprises to innovate and transform using digital technologies. There should be increased investment in urban infrastructure, especially information infrastructure, increased investment in innovation, and strengthened interaction and connections with other cities.

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Conflict of Interest

The authors declare no conflict of interest.

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